Pesticide Illness Among Flight Attendants Due to Aircraft Disinsection

Patrice M. Sutton, MPH,[1†] Ximena Vergara, MPH,[1‡] John Beckman, BS,[1‡] Mark Nicas, PhD, CIH,[2§] and Rupali Das, MD, MPH[3*¶]

Background *Aircraft "disinsection" is the application of pesticides inside an aircraft to kill insects that may be on board. Over a 1-year period, California's tracking system received 17 reports of illness involving flight attendants exposed to pesticides following disinsection.*
Methods *Interviews, work process observations, and a records review were conducted. Illness reports were evaluated according to the case definition established by the National Institute for Occupational Safety and Health.*
Results *Twelve cases met the definition for work-related pesticide illness. Eleven cases were attributed to the "Residual" method of disinsection, i.e., application of a solution of permethrin (2.2% w/w), solvents (0.8%), and a surfactant (1.4%); the method of disinsection could not be determined for one case.*
Conclusions *The aerosol application of a pesticide in the confined space of an aircraft cabin poses a hazard to flight attendants. Nontoxic alternative methods, such as air curtains, should be used to minimize disease vector importation via aircraft cabins. Employers should mitigate flight attendant pesticide exposure in the interim.* Am. J. Ind. Med. 50:345–356, 2007. *© 2007 Wiley-Liss, Inc.*

KEY WORDS: Occupational pesticide illness; flight attendants; aircraft disinsection; residual disinsection; permethrin; air curtains

INTRODUCTION

Aircraft disinsection is the application of pesticides inside an aircraft to kill insects that may be on board. Disinsection is undertaken as a public health measure to address the potential threat posed by insects to the health of humans, plants, animals, and agriculture [Gratz et al., 2000; USDOT, 2006]. Airlines are required to perform this procedure to comply with quarantine regulations of some countries. Currently 21 countries require aircraft disinsection of all (N = 16) or selected (N = 5) inbound flights. Of the 16 countries that currently require disinsection, nine require the pesticide to be applied while passengers are on board, and seven permit the use of an aerosolized spray while passengers are not on board. Most countries reserve the right to require disinsection should they perceive a threat to their public health, agriculture, or environment [USDOT, 2006].

[1]Public Health Institute, Oakland, California
[2]School of Public Health, University of California, Berkeley, California
[3]Occupational Health Branch, California Department of Health Services, Richmond, California
Institution where the work was performed: California Department of Health, Services, Occupational Health Branch, 850 Marina Bay Parkway, Building P, 3rd Floor, Richmond, CA 94804 (510) 620-5757 Fax (510) 620-5743.
†Research Scientist.
‡Research Associate.
§Adjunct Professor.
¶Public Health Medical Officer.
Contract grant sponsor: This work was performed under a Cooperative Agreement, California Sentinel Event Notification System for Occupational Risks (SENSOR), between the California Department of Health Services Occupational Health Branch and the National Institute for Occupational Safety and Health; Contract grant sponsor: Cooperative Agreement; Contract grant number: U60/CCU902990.
*Correspondence to: Rupali Das, Occupational Health Branch, California Department of Health Services, 850 Marina Bay Parkway, Building P, 3rd Floor, Richmond, CA 94804 USA. E-mail: rdas@dhs.ca.gov.

Accepted 24 January 2007
DOI 10.1002/ajim.20452. Published online in Wiley InterScience (www.interscience.wiley.com)

In 1996, the U.S. Environmental Protection Agency (USEPA) determined that the benefit of disinsection in occupied cabins may not exceed the risk, and that such use may result in unreasonable adverse effects on the environment [USEPA, 1996]. The U.S. government does not require any disinsection procedure to be performed [USDOT, 2006], and although the procedure is not explicitly prohibited, there are no pesticides registered for use in the U.S. for aircraft disinsection [USEPA, 2001].

There are two approaches to disinsection used in the airline industry: the pesticide is applied by flight attendants in the presence of passengers after the plane leaves the gate (Blocks-Away) and/or before it lands (Top-of-Descent), or the pesticide is applied by ground crew prior to passenger and flight crew boarding (Pre-Flight and Residual). Whereas the Blocks-Away, Top-of-Descent, and Pre-Flight applications are short-lived, the Residual application leaves a long-lasting (56 days) pesticide residue in the aircraft cabin. Notification for in-flight applications states that the spray is ''nontoxic,'' and there is no passenger notification for Residual applications.

Recommended procedures for aircraft disinsection are established by the World Health Organization (WHO) Expert Committee on Vector Biology and Control [WHO, 1985a,b, 1995]. All methods of aircraft disinsection involve applying a synthetic pyrethroid, either permethrin or *d*-phenothrin, inside the aircraft cabin. Pyrethroids are synthetic derivatives of natural pyrethrin compounds and are widely used as broad-spectrum insecticides [Ray and Forshaw, 2000; Bradberry et al., 2005]. Both pyrethrins and pyrethroids exert their toxic effects by prolonging the inactivation of sodium channels in the peripheral and central nervous systems [Coats, 1990; Ray, 1991; He, 1994; Bradberry et al., 2005]. Exposure to synthetic pyrethroids can cause abnormal sensations on exposed skin, contact dermatitis, dizziness, nausea, anorexia, fatigue, mild disturbances of consciousness, muscular fasciculations, and, at high doses, pulmonary edema, convulsions, and coma [He et al., 1989; Bradberry et al., 2005; Spencer and O'Malley, 2006]. Pyrethroid pesticides are highly toxic to insects as well as to aquatic life [Weston et al., 2005]. Acute toxicity in mammals is limited because pyrethroids are rapidly detoxified in the blood and liver to their inactive components [Ray and Forshaw, 2000].

The signs and symptoms of exposure to permethrin include irritation of the eyes and upper respiratory tract; irritation, burning, and itching of the skin; and urticaria [Kolmodin-Hedman et al., 1982; Fuortes, 1999]. Aerosolized pyrethroid insecticides used for disinsection may trigger non-specific bronchoconstriction and respiratory symptoms in asthmatics [WHO, 1995]. In its most recent evaluation of the safety of pyrethroids used for aircraft disinsection, WHO concluded ''paraesthesias and, in inhalation exposure, upper respiratory tract irritation, . . . may occur among aircraft passengers and crew after in-flight spraying and among crew after pre-flight spraying . . . [and] while they may cause transient discomfort, pyrethroids do not indicate or predict serious health effects'' [WHO, 2005].

The California Department of Health Services (CDHS) Occupational Health Branch conducts statewide surveillance of acute work-related pesticide illness as part of the National Institute for Occupational Safety and Health (NIOSH) Sentinel Event Notification System for Occupational Risk (SENSOR) Program. CDHS performs investigations of selected pesticide illness incidents to identify the causes of illness and to develop recommendations for primary prevention of future illnesses. Between August 2000 and August 2001, CDHS received physician reports of six incidents involving 17 flight attendants who reported exposure to pesticides used during aircraft disinsection. All incident reports involved flight attendants working on 747–400 aircraft for a single employer. CDHS undertook an investigation to: (1) determine if the reported illnesses were caused by pesticide exposure; (2) identify factors that may have contributed to documented illnesses; and (3) make recommendations to prevent pesticide poisoning.

MATERIALS AND METHODS

Data Collection

The SENSOR program collected existing health and hazard data pursuant to legislative authority of the CDHS (California Health and Safety Code 105175; 100325; and 100330). SENSOR protocols have been approved by the California Health and Human Services Agency Committee for the Protection of Human Subjects.

To investigate the reports of illness among flight attendants following aircraft disinsection, SENSOR project staff attempted to interview all 17 flight attendants with a reported illness. Flight attendants were phoned at least three times at their homes and once contacted they were asked to participate in a voluntary telephone interview. On initial contact with workers, project staff read them an informed consent script and sought their verbal consent to participate. Workers who agreed to participate were surveyed using a structured questionnaire in which workers were queried about their incident-specific work duties, exposures, signs and symptoms, and medical follow-up. In addition project staff: (1) requested medical records from the treating physician(s) for all 17 flight attendants; (2) conducted an on-site investigation at the employer's aircraft maintenance center, including a walk-through of a 747–400 aircraft; (3) interviewed employer and employee representatives using a detailed industrial hygiene checklist about the aircraft disinsection work process, tasks, and exposure control measures; (4) viewed a video that documented the Residual disinsection of a 747–400 aircraft; and (5) reviewed the employer's written records about aircraft disinsection, including: the pesticide products used, application policy and procedures, safety and health programs, results of industrial hygiene monitoring conducted by the employer, aircraft ventilation rates, logs of visits to the employer's medical facilities in San Francisco and Los Angeles, and additional reference material.

Evaluation Criteria

All illness reports were evaluated according to: (1) NIOSH guidelines for evaluation of pesticide illness [NIOSH, 2005]; (2) the presence of one or more routes of pesticide exposure; and (3) the presence, use, and efficacy of measures to limit flight attendant pesticide exposure. NIOSH defines a case as acute onset of symptoms that are consistent with the pesticide formulation, and that involve systemic signs or symptoms, dermatologic lesions, and/or ocular lesions. A report was classified as work-related pesticide illness if all of the following criteria were met: (1) exposure occurred while working; (2) the exposure was documented; (3) two or more adverse health effects were documented; and (4) there was evidence in the scientific literature that supported a causal relationship between pesticide exposure and adverse health effects.

Data Analysis

An occupational health physician and industrial hygienist reviewed available medical, worker interview, and employer records for all illness reports. Descriptive statistics were used to analyze the illness and industrial hygiene data. A mathematical model was developed to estimate the air levels of permethrin during and immediately after the pesticide application. A complete description of the methodology for the model is presented in Appendix A.

RESULTS

Data Collection

Of 17 flight attendants with a reported illness, six completed interviews, eight declined participation, and three could not be reached. CDHS interviewed eight employer representatives, and five employee representatives from the Association of Flight Attendants (AFA). Employer representatives included two of three industrial hygienists who collected the employer exposure data, and other personnel responsible for implementation of the aircraft disinsection procedures. CDHS obtained symptom data for 15 flight attendants through medical records and/or telephone interviews.

Illness Reports

A total of 12 of 17 flight attendants met the NIOSH definition for work-related pesticide illness based on: (1) timely, self-reported evidence of exposure made to a licensed health care professional; (2) the presence of two or more new post-exposure abnormal health effects (symptoms reported by a worker, signs reported by a licensed health care provider) and/or test or laboratory findings; and (3) health effects that are consistent with the known toxicology of the pesticide applied to the aircraft [NIOSH, 2005]. For five illness reports, there was insufficient information available to confirm or rule out that the flight attendants' illnesses were pesticide-related.

The sources of data, medical information, and exposure characteristics of the 12 cases are presented in Table I. The 12 cases involved three separate incidents that occurred between August 2000 and March 2001. Two incidents involved 1 flight attendant each, and the third involved 10 flight attendants. Two incidents (11 cases) involved a Residual application of permethrin. In the third incident, the method of disinsection could not be determined by CDHS. All 12 cases of pesticide illness involved exposure to a pesticide that was applied on aircraft in Australia (Sydney) prior to traveling to the U.S. (Los Angeles).

Of the 12 cases, eight flight attendants experienced symptoms immediately or shortly after boarding the aircraft and two within an hour of boarding. Specific information on the timing of onset of symptoms was missing for two flight attendants. The most common signs and symptoms experienced were respiratory ($N = 12$), nervous system ($N = 11$), dermatological ($N = 9$), eye ($N = 9$), cardiovascular ($N = 5$), and gastrointestinal ($N = 6$) (Table II).

There were no incident-specific, quantitative exposure data available. In two incidents documented by CDHS, flight attendants were exposed to the aircraft cabin 45 min. (1 case) to two hours (10 cases) after a Residual application was completed. The precise time between disinsection and flight attendant exposure could not be determined for the third incident (1 case). Of 12 flight attendants who became ill, four detected odor at the time of their exposure. For one incident (involving 10 flight attendants), it was reported that pesticide residues were visible on aircraft cabin surfaces.

Pesticide Application Work Process

A description of the sequence of the Residual disinsection work process is presented in Table III.

Disinsection

The Residual disinsection process involved spraying the aircraft cabin and cargo hold with 34.4 liters (L) of a solution of 2.2% by weight (w/w) permethrin (25:75 *cis*:*trans*), 0.8%

TABLE I. Sources of Data, Medical Information, and Exposure Characteristics of Three Incidents of Pesticide Poisoning Due to Aircraft Disinsection (N = 12 cases)

Characteristic	Incident 1	Incident 2	Incident 3
No. of cases[a]	10	1	1
Type of pesticide application	Residual	Residual	Unknown
Time from exposure to symptom onset	Immediately upon boarding (N = 7) Within 1 hr. of boarding (N = 2) Unknown (N = 1)	Unknown	Immediately upon boarding
Number sought Medical care	10	1	1
Time from symptom onset to Medical care	Less than or equal to 1 day (N = 10)	2 days	1 day
Medical diagnosis by a physician at office visit	Possible permethrin exposure (N = 1) Pesticide exposure (N = 1) Post-prolonged insecticide fume [sic]/ exposure to permethrin (N = 8)	Pesticide inhalation toxicity	Exposure to permethrin
Pre-existing health conditions	Unknown or not reported (N = 9) Recent sinus symptoms (N = 1)	Atrial Fibrillation (N = 1)	Self-reported Multiple Chemical sensitivity (N = 1)
Number of medical records reviewed by CDHS	10	1	1
Number of workers interviewed by CDHS	4	0	1
Employer written documentation of when aircraft disinsection occurred	Yes	Yes	Unknown
Time between completion of disinsection and flight attendant boarding	2 hr	45 min	Unknown
Type of post-disinsection ventilation	Mechanical dilution ventilation via the air-conditioning system with recirculation of cabin air (~11 air changes per hour)	Unknown	Unknown
Adherence to post-disinsection 1-hr. aircraft ventilation requirements	Yes	No	Unknown
Puddles and/or damp surfaces observed by flight attendants	Yes	Unknown	Unknown
Odor detected at time of exposure	Yes (N = 3)	Unknown	Yes (N = 1)

[a]Standardized severity classification criteria were applied to pesticide illness cases (NIOSH, 2005). For the 12 cases reported in this paper, 7 were classified as "moderately severe" and 5 as "mild.".
Unknown = missing data.

organic solvent carrier, 1.4% nonoxinol 9 (an emulsifier/ surfactant), and 95.6% water. The pesticide solution was mixed by pouring 700 ml of the product (an emulsifiable concentrate) into each of two 16.5 L containers of water. The pesticide solution was mixed and loaded outside the aircraft. Next, it was poured into two types of application equipment: (1) ultra-low volume (ULV) spray-mist "Cold Fogging" applicators (Curtis DYNA-FOG Tornado ULV Model 2895 with Model 3000 Flex Hose. P.O. Box 297, 17335 US 31, North Westfield, IN 46074-0297, USA) which were pulled through the aircraft on wheeled carts; and (2) a hand-held sprayer (B&G Model 1010 with Trigger TEEJET valve and 80° fine sprayer, 6.4 ounces per minute. B&G Chemicals & Equipment Co., Inc. Dallas, TX). The foggers were used for most surfaces (e.g., seats, walls, overhead compartments), and the hand-held sprayer was used for the galleys, crew rest (bunk) area, bathrooms, cockpit, carpet, and cargo hold. Approximately, 29 L of the pesticide solution was applied to the passenger and crew sections of the aircraft, and the remaining 5.4 L was applied to the cargo hold. The disinsection process was conducted by three applicators in about 35–45 min. From zero to 15 min. after the Residual pesticide application was completed the aircraft was ventilated (Table III). The minimum ventilation period required by the employer was 1 hr. For one of the incidents documented by CDHS (10 cases), the air conditioning system was used for ventilation, and the aircraft was ventilated for at least 1 hr. In this incident, air was re-circulated throughout the cabin during the ventilation period. For the other two incidents (2 cases), CDHS could not determine the type of ventilation used (i.e., natural ventilation and/or the air conditioning system) or the duration of the ventilation period. Following the ventilation period, the aircraft was towed to the gate, and the flight crew boarded the aircraft.

TABLE II. Signs and Symptoms Among 12 Flight Attendants* with Pesticide-Related Illness from Aircraft Disinsection

Signs	No.
Respiratory	
✓ Runny nose	1
✓ Upper respiratory pain/irritation	1
✓ Wheezing	1
Eye	
✓ Conjunctivitis	2
Skin	
✓ Erythema/flushing	1
Symptoms	**No.**
Cardiovascular	
Palpitations	5
Skin	
✓ Pruritis	5
✓ Irritation/pain	4
✓ Erythema/flushing	2
✓ Edema/swelling	1
✓ Rash	1
Eye	
✓ Pain/irritation/inflammation	8
Lacrimation	3
Pruritis	2
Gastrointestinal	
✓ Nausea	5
✓ Anorexia	3
Abdominal pain/cramping	1
✓ Diarrhea	1
✓ Vomiting	1
Renal/genitourinary	
Polyuria	1
Oliguria/anuria	1
Miscellaneous	
✓ Fatigue	1
Nervous/sensory	
✓ Headache	9
✓ Hyperactivity/anxiety/irritability	6
✓ Tingling hands/feet/elsewhere	6
✓ Dizziness	5
Ataxia	4
Confusion	4
Muscle weakness	4
Profuse sweating	3
✓ Fasciculations	2
Muscle rigidity	2
Slurred speech	2
Respiratory	
✓ Shortness of breath	7
✓ Upper respiratory pain/irritation	6
Cough	4
Pain on deep breathing	4
✓ Runny nose	3
✓ Wheezing	1

*More than one symptom or sign may have been reported by one individual.
✓ Sign or symptom related specifically to permethrin or generally to pyrethroid exposure reported in the published literature [Flannigan et al., 1985; He et al., 1989; USEPA, 1999; Kolmodin-Hedman et al., 1982; Fuortes, 1999; Bradberry et al., 2005; Spencer and O'Malley, 2006].

Pesticide Exposure Control Measures and Training for Flight Attendants

Exposure control measures were: the employer's disinsection protocol specified a minimum of 1 hr. of ventilation after the pesticide application, accomplished by opening the cabin doors and/or provided by the aircraft's air conditioning system (up to a maximum of 11 air changes per hour (ACH)); and the pesticide application was performed by ground crew before flight attendants boarded the aircraft. No personal protective equipment was required, recommended, or in use by flight attendants. Flight attendant training regarding the procedure consisted of one page of information in the flight attendant's manual and a fact sheet on the issue distributed by the employer in November 2000.

Non-Incident-Related Ambient Levels of Permethrin

There were no environmental samples collected from the aircraft involved at the time that these incidents occurred. The available data were limited to permethrin levels in 136 samples collected by the employer from these or similar aircraft (747−400s) following the same Residual disinsection procedures conducted at other times. Between April 1997 and May 2001, the employer health and safety staff collected 64 surface wipe samples (i.e., from arm rests, walls, floor runners), 23 pieces of fabric and materials (i.e., seat covers, carpet, blankets, headsets, tissues, paper towels), and 49 area air samples. The employer conducted the industrial hygiene evaluation to monitor flight attendant pesticide exposure and in response to flight attendants' expressed health concerns related to aircraft disinsection. Aircraft tested by employer health and safety staff were reportedly selected based on convenience and were considered to be representative of typical conditions. Samples were collected from a total of 11 planes from 15 min. up to 28 hr. after the aircraft were disinsected in Sydney with 34.4 L of a 2.2% permethrin solution. In September 2001, four additional surface wipe

TABLE III. Residual Disinsection Work Process

	Work process					
	Pre-disinsection cleaning	**Disinsection**	**Ventilation**[a]	**Aircraft towed to gate**	**Aircraft positioned at gate**	**Flight crew boards**
Workers on aircraft:	Cleaners	Applicators	Maintenance	Maintenance	Maintenance, cleaning, catering, other ground crew	Flight crew, maintenance, cleaning, catering, ground crew
Door status:	Unknown	Doors closed except for entry door	Doors open if only natural ventilation used Doors closed if air conditioning system used for ventilation	Doors closed	One or more doors open	One or more doors open
APU[b]/air conditioning status:	Unknown	APU off; air conditioning off	APU off and air conditioning off for 0-15 min.; APU off and air conditioning off if only natural ventilation used; APU started and air conditioning on if being used for ventilation	APU on; air conditioning on	APU on; air conditioning on	APU on; air conditioning on

[a]To ventilate the aircraft, one or both of the following methods were permitted: (1) the doors to the aircraft were opened (i.e., "natural ventilation") and no supplemental ventilation was used, and/or (2) the doors to the aircraft were closed and the air conditioning was turned on with the re-circulating fans off.
[b]APU = auxiliary power unit. The APU is a small gas turbine mounted in the tail cone of the aircraft with an electric generator supplying electric power to the aircraft when the plane is on the ground. The APU supplies airflow to three air-conditioning packs that cool and dehumidify the cabin air.

samples were collected by a flight attendant from one aircraft subsequent to Residual disinsection.

Permethrin levels on surfaces, fabric, and materials (N = 91) were highly variable, with six orders of magnitude difference between the lowest and highest levels (range 15–35,980,000 micrograms per square meter ($\mu g/m^2$) (mean = 589,313 $\mu g/m^2$; median 1600 $\mu g/m^2$)). Permethrin was detected on aircraft cabin surfaces up to 28 hours after the pesticide was applied. No samples were collected later than 28 hours after the pesticide application. Ninety-five percent of the samples of surface, fabric, and other materials were 1,596,104 $\mu g/m^2$ permethrin or less. The highest level of permethrin (35,980,000 $\mu g/m^2$) was measured on carpet associated with a visible residue on the cabin floor.

Nineteen of 22 air samples (86%) collected in the time period beginning at the completion of the pesticide application up to approximately four hours post-disinsection had detectable levels of permethrin (range 2.2–1040 micrograms per cubic meter ($\mu g/m^3$)). The highest level of permethrin measured in air (1040 $\mu g/m^3$) was in a sample collected during the period approximately 15–96 min. post-disinsection. Permethrin was not present at levels above the limits of detection in any of the 27 air samples collected in the time period 3–28 hr. after disinsection (LOD for 33 samples = 0.15 $\mu g/m^3$; LOD for 16 samples was not reported).

Modeling of the Pesticide Release in the Aircraft Cabin

The results of the model estimating the concentration of permethrin in the aircraft cabin air during the pesticide application (0–30 min.) and during the 45-min. period following the application are presented in Figure 1. Two scenarios were evaluated in the model: (1) no mechanical dilution ventilation was supplied to the aircraft cabin in the 45-minute period after the application ended (0 ACH); and (2) 11 ACH was supplied in the 45-minute period following the application. The model assumed: (1) a solution containing 2.2% permethrin (w/w) was applied with a fogger in the cabin; (2) passenger cabin volume of 1,000 m^3; (3) average cabin height of six feet; (4) equal permethrin mass in different intervals of particle diameter in the range 5–40 μm; (5) uniform emission during the 30-minute spray period; and (6) no ventilation whatsoever in the cabin during the application. The model accounted for the differential gravitational settling rates of particles with different aerodynamic diameters.

The permethrin concentration in the aircraft cabin at the end of the application was estimated to be 91,178 $\mu g/m^3$, based on the mass of permethrin released over time, the cabin air volume, the gravitational settling rates of the different-sized particles containing permethrin, and the rate of ventilation in the aircraft cabin. Forty-five min. after the

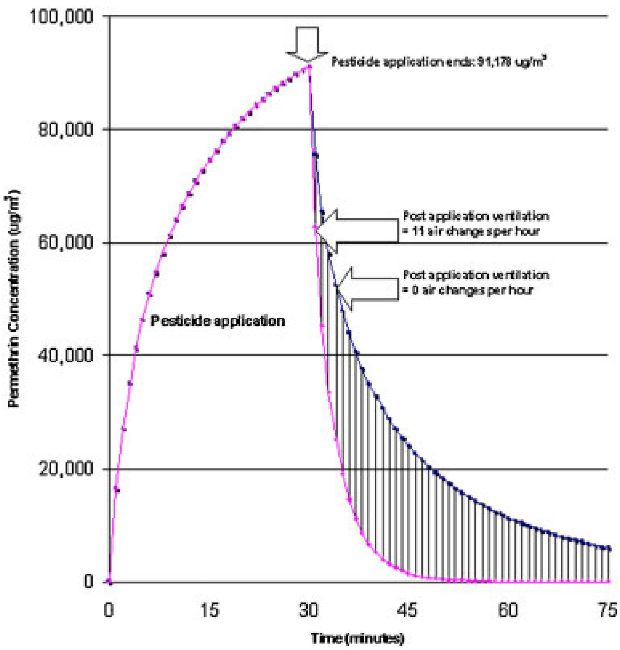

FIGURE 1. Model of permethrin levels in aircraft cabin air during and 45 min. after Residual disinsection (29 L of 2.2% permethrin applied). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

application was completed, the air concentration of permethrin was estimated to be 5988 $\mu g/m^3$ if there was no supplied mechanical ventilation (0 ACH), and 1.6 $\mu g/m^3$ if 11 ACH were supplied to the aircraft.

DISCUSSION

Flight Attendant Illness

The 12 cases documented in this report demonstrate that Residual insecticide applications can result in acute illness among workers exposed to the aircraft cabin environment after disinsection. All 12 cases met the NIOSH definition of work-related acute pesticide poisoning. The evidence supporting the role of pesticide exposure in causing the illnesses in these incidents includes: (1) all of the illnesses occurred shortly after the onset of pesticide exposure; (2) all of the illnesses were documented by a licensed health care practitioner; (3) all cases experienced recognized signs and/or symptoms of exposure to permethrin; and (4) illnesses were documented in three separate incidents (Tables I and II). These illnesses are also consistent with acute human health effects experienced by workers exposed to pyrethroids in other occupational settings [He et al., 1989]; in the seven-year period 1998–2004, CDHS' SENSOR program identified 230 cases of work-related illness due to pyrethroid exposure in other non-aircraft work settings.

Documented Health Effects of Cases

Many, but not all, of the health effects experienced by the flight attendants were consistent with recognized health effects specific to permethrin or generally to pyrethroid exposure (Table II). In order to be considered a case, our surveillance criteria require the presence of two health effects (signs or symptoms) that are consistent with the health effects of the active pesticidal ingredient as reported in the peer-reviewed literature [NIOSH, 2005]. Individuals may exhibit a wide variety of signs and symptoms following pesticide overexposure. The flight attendants described in this paper were exposed to a pesticide formulation that included permethrin, solvents, and a surfactant. Any of these constituents may have contributed to health effects, but the relative contribution of each component is not known. Some the health effects reported by the flight attendants may also be caused by anxiety and be observed with mass psychogenic illness [Lessenger, 1992; Jones et al., 2000; Henningsen et al., 2003]. However, because a pesticide formulation capable of causing the symptoms was present in all cases, anxiety and, mass psychogenic illness are unlikely explanations for the symptoms [House and Holness, 1997; Jones, 2000].

Nature and Extent of Illness Due to Disinsection

The 12 cases of pesticide illness documented by CDHS are the first reports of acute adverse human responses to aircraft disinsection reported in the scientific literature. CDHS' documentation of these cases occurred because the workers sought medical care in a state with an occupational health surveillance system, their physicians reported the illnesses as required by law, and CDHS had the mandate and capacity to conduct a follow-up investigation to link the reported illnesses with the circumstances in which the exposures occurred. This underscores the critical role of public health surveillance as an early warning system to identify unrecognized harmful exposures and health effects and to formulate and disseminate prevention strategies. The documented acute illnesses from aircraft disinsection in this report underestimate the magnitude of illnesses due to this procedure. According to self-reports collected and compiled by the Association of Flight Attendants (AFA), flight attendants (and, in some cases, passengers and pilots) reported symptoms consistent with exposure to pyrethroid pesticides on 237 flights from August 1, 2000 to July 31, 2001 (Association of Flight Attendants. Memorandum to Patrice Sutton from Judith Murawski. September 13, 2002). Of these, 224 (95%) followed Residual spray applications. During the calendar years 2000 and 2001, there were 38 cases of "insecticide poisoning" among flight attendants based in

Los Angeles as recorded on the employer's illness and injury logs and reviewed by CDHS. Moreover, CDHS did not assess the pesticide exposures incurred by the applicators in Sydney. These workers may incur the highest exposures from this procedure, depending on the presence, use, and efficacy of measures implemented to control their exposures.

The true nature and extent of health impacts of disinsection are unknown because notification regarding the exposures and surveillance measures to comprehensively track the required data are lacking. In general, cases of work-related pesticide illness are seldom reported and verified, because substantial barriers to reporting exist [Azaroff et al., 2002]. An individual must recognize they have been exposed to a pesticide, know the signs and symptoms of pesticide illness, and seek medical care. Flight attendants received minimal training regarding their pesticide exposure; and cleaners, caterers, mechanics, and other workers who routinely entered newly pesticide-treated aircraft (Table III) were not recognized as being pesticide-exposed. Therefore, workers may not have made the connection between their exposure and symptoms. The treating physician must also recognize and report the illness to a local health agency. The signs and symptoms of pesticide-related illness may be nonspecific, and, therefore, may be misdiagnosed. Workers' fear of employment-related retaliation also prohibits full reporting.

Flight Attendant Exposure Associated With Residual Disinsection Application Process

The highest permethrin level in cabin air documented by the employer in this investigation was 1040 μg/m^3, measured over the 81-minute interval beginning 15 min. after Residual disinsection. In a study of Pre-Flight and Top-of Descent aircraft disinsection applications, mean levels of *d*-phenothrin in area samples measured over the period including the spraying operation and a time of 40 min. afterwards were in the range of 133–1203 μg/m^3 [Berger-Preiss et al., 2006]. WHO estimates that Pre-Flight and Top-of-Descent disinsection results in a momentary maximal concentration of permethrin or *d*-phenothrin in aircraft air of 7000 μg/m^3, with a considerably higher concentration close to the nozzle of the spray can, and a rapid drop in the concentration after the spraying [WHO, 2005].

These data on flight attendant exposure are one to two orders of magnitude higher than maximum personal air monitoring exposure levels of workers in a variety of other settings where permethrin is used [Kolmodin-Hedman et al., 1982; Edling et al., 1985; Llewellyn et al., 1996]. This qualitative comparison illustrates the relatively high exposure levels potentially incurred by flight attendants on aircraft where disinsection takes place, and that passenger exposure associated with disinsection may exceed occupational exposure levels in other settings.

Treated surfaces are also a pathway of exposure to pesticides used for disinsection. Residual disinsection involves intentionally spraying virtually all of the physical space in an aircraft, including surfaces and materials, seats, carpets, and bunks, and leads to pesticide residues in the aircraft cabin. The non-incident-related employer sampling data documented that highly variable surface levels of permethrin were prevalent throughout treated aircraft up to 28 hours post-disinsection, with the variability of residues partly due to the differential collection efficiencies among surface types and the lack of a standardized sampling method [NAS, 2002]. Although, dermal uptake of pyrethroids is reported to be relatively low [Ray, 1991], results of case studies of indoor exposures to other low-volatility pesticides indicate that direct skin contact with contaminated textiles significantly contributes to total body exposure [Gebefügi, 1989].

These data demonstrate that Residual disinsection application process results in pesticide residues in the aircraft air and virtually all of its physical space. Pesticide illness can result if exposure to a treated aircraft cabin occurs in the absence of adequate control measures.

Factors That Contributed to Documented Cases

The accepted strategy for controlling toxic workplace exposures is to first attempt to eliminate the generation source, hazardous materials, and dangerous activities [Burgess, 1994]. When pesticide use is not or cannot be eliminated, most techniques designed to increase safety focus on the isolation of the chemical from the worker [Keifer, 2000]. In contrast, Residual disinsection involves placing flight attendants in a pesticide-treated workplace with few industrial hygiene measures to minimize exposure and no egress from the treated area.

Control of flight crew pesticide exposure in general, and specifically for these 12 cases, relied exclusively on the degree and duration of post-disinsection aircraft ventilation. The mathematical model illustrates the influence of the air exchange rate and duration of ventilation on the amount of pesticide residues in the air (Fig. 1). Other factors such as equipment leaks [Llewellyn et al., 1996], application equipment that is not calibrated, and ambient temperature and humidity will impact the distribution of pesticide levels on surfaces and in the air within and among treated aircraft.

Prior to these incidents, the employer had taken steps to improve the safety of the required procedure by establishing a minimum 1-hr. post-application ventilation period. However, the exclusive use of the ventilation system at maximum capacity was not specifically mandated in writing (Table III), and there were no quality control or other requirements to document that after every application at least 1 hr. of such dilution ventilation had occurred.

In one incident (10 cases), the required one-hour of ventilation using the air conditioning system was implemented, and the flight crew boarded the aircraft 2 hr. after the Residual application was completed. Despite these measures, some of the 10 flight attendants observed pesticide residues and/or detected odor. The only deviation from standard procedures identified by the employer in this incident was during the ventilation period, cabin air was recirculated, instead of being supplied with 100% fresh air. However, the Residual pesticide application results in aqueous, spherical particles in the range of 5 μm or greater, and virtually all of the particles are likely to be removed by the HEPA filters present on a 747-400 aircraft. Therefore, recirculating the aircraft air did not contribute to a significant increase in flight attendant exposure. These 10 cases indicate that, although the standard (1 hr) ventilation procedures were likely to have reduced flight attendants' exposures, the procedures were not fully effective. For the second incident, the flight attendant boarded the aircraft 45 min. after the application, before the required one-hour ventilation period. There was insufficient information to assess what additional factors may have contributed to the flight attendant's illness in the third incident.

We conclude that inadequate post-disinsection aircraft ventilation procedures and a lack of quality assurance measures contributed to the documented adverse health impacts. Conditions for adverse health impacts may have been present on other flights not reported to CDHS. Employer records of non-incident-specific sampling data document that the "disinsection application crew did not always follow established procedures" and that "natural ventilation is insufficient to assure that all damp surfaces are dry prior to the crew boarding."

Worker illness may have been exacerbated because flight attendants were unable to remove themselves from exposure and seek medical care in a timely way. The primary intervention in the case of a toxic exposure is to remove the affected individual from the area of exposure as soon as possible [Lessenger, 1992]. Residual disinsection results in unavoidable flight attendant exposure to a pesticide in a confined space (i.e., a relatively small, enclosed area with no ready egress). Therefore, the most important treatment of any toxic syndrome, interruption of exposure [Fuortes, 1999], is precluded by the conditions of use.

WHO recommendations for disinsection are based on two health-related assumptions: (1) the human toxicity of permethrin is low; and (2) the conditions of use will result in exposures to concentrations too low to cause acute illness [WHO, 1985a,b, 1995, 2005]. The findings of this investigation illustrate that relatively "low-toxicity" chemicals can result in hazardous exposures as a consequence of the way a chemical is used in practice. It is therefore imperative to gather workplace data to validate assumptions related to occupational exposures, and to identify and consistently implement measures capable of protect the health of exposed workers.

LIMITATIONS

There were important limitations to this investigation. Factors not identified by CDHS may have contributed to these illnesses. Our understanding of the Residual disinsection procedure at the time of these incidents was based on information pieced together from the employer's data (i.e., written documentation of the procedures, audits, air monitoring reports, and a video of the standard procedure), incident-specific medical records and other illness reports, and interviews with flight attendants and employer staff with in-depth, first-hand knowledge of the procedure and/or incidents. Although the employer confirmed that CDHS' process description was accurate, as in any workplace, only the workers who actually applied the pesticide had direct knowledge of what occurred. Therefore, we cannot rule out that other, unrecognized factors (e.g., the pesticide was not mixed or applied according to procedures) contributed to these illnesses. This seems unlikely to have occurred for at least one incident (10 cases). In this incident, the employer conducted a timely investigation.

The amount of pesticide exposure incurred by flight attendants in the incidents reported by CDHS is not known. There were no incident-specific personal-exposure monitoring data for the cases. However, the existing samples were all collected in real-time, under representative workplace conditions, include a very large number of samples from multiple aircraft over time, and virtually all were collected by industrial hygiene professionals. As such, the samples provide evidence of the magnitude and route of flight attendant exposure, which occurred via inhalation and through contact with treated surfaces.

Although we attempted to contact all flight attendants, only 5 of 12 cases (42%) were interviewed by CDHS. Such a low response rate is consistent with the interview rate for a passive surveillance system and does not suggest a systematic unidentified cause for low worker participation. In general, a limitation of passive surveillance systems is that there can be a time delay between when an incident occurs, and when reports are received, processed, and investigated. For two of three incidents (11 cases), 6–8 months had elapsed between the time of the incidents and the interviews. For the third incident (1 case), 3 weeks had elapsed between the time of the incident and the interview, which in this case was completed successfully. The delay in interviewing the workers did not introduce recall bias into the case classification. All 12 cases sought medical care from a licensed health care provider within 2 days or less after the onset of symptoms. For all 12 cases the medical information recorded at the time of the incident served as the main source of data regarding health effects. Other factors that may have influenced the response rate were that the interviews were solicited by telephone, and the workers had no previous contact with CDHS and therefore had not established a basis of trust with us. Finally, workers were difficult to reach because they lived in other states and had irregular work-schedules. In general, fear of job loss is a barrier to worker participation in occupational health investigations. We are unable to identify which, if any, of these potential barriers to participation impacted the response rate.

Finally, our assessment did not take into account the potential long-term effects of repeated low-level exposures to pyrethroid pesticides. One study of 33 self-selected, pesticide-exposed flight attendants, reported that nearly half had three or more abnormal neurobehavioral functions [Kilburn, 2004]. Permethrin is considered a potential carcinogen by the USEPA [USEPA, 1997], and the International Agency for Research on Cancer states there is inadequate evidence in animals to classify the carcinogenicity of permethrin in humans [IARC, 1991].

CONCLUSIONS

The 12 cases of pesticide illness documented in this investigation demonstrate that Residual insecticide applications can result in illness among workers exposed to the aircraft cabin environment after disinsection. The documented acute illnesses likely underestimate the magnitude of illnesses due to disinsection. The public health impact of Residual disinsection also includes other workers who pilot, clean, service, and maintain the aircraft, and the passenger population. The conditions of use (i.e., the aerosol application of a pesticide in a confined space) significantly contributed to the human health hazard of Residual disinsection. Therefore, the replacement of permethrin with another chemical alternative would not eliminate the health hazards of disinsection.

The prevention of vector-borne diseases remains essential to protecting public health. An alternative to the use of insecticides for disinsection that obviates the health concerns of current practices is the ‘‘air curtain’’ [USDOT, 2004; Carlson et al., 2006]. Air curtains direct air currents at a doorway to exclude insects, a procedure analogous to the use of a hand-held fan for fly control [USDOT, 2004]. Researchers at the U.S. Department of Agriculture have validated the concept that air barriers can effectively prevent the passage of flying insects into an aircraft [Carlson et al., 2006]. National and international health agencies should recommend nontoxic alternative methods of minimizing the importation of disease vectors in aircraft cabins, such as air curtains.

Until non-toxic alternatives are adopted or sanctioned by countries that require disinsection, airline employers should take steps to mitigate flight attendant pesticide exposure. It is important to note that, although these interim measures are expected to increase protection for potentially exposed individuals, they may not be entirely effective in preventing exposure to pesticide formulations. Airline industry employers should: educate all potentially exposed workers about the hazards of aircraft disinsection; restrict entry for all workers to the aircraft cabin for at least 4 hr. after disinsection; implement, document, and enforce maximal ventilation procedures on every treated aircraft; conduct industrial hygiene sampling to validate the efficacy of a restricted entry interval and maximal ventilation procedures in mitigating airborne exposures, wet surfaces and/or puddles, or other avenues for dermal exposure; institute quality control measures for every pesticide application, including a policy of not boarding aircraft that lack written documentation of compliance with pesticide exposure control measures; seek permission from the relevant national quarantine authorities to cease spraying pesticides in the crew rest area (bunk room), an area that encompasses both minimal air flow and potentially maximal contact with treated surfaces; notify in advance passengers who may be exposed to a pesticide-treated aircraft of the procedure and the potential health risks; schedule flights to countries that require disinsection so that the number of aircraft treated is minimized; and initiate active illness surveillance among exposed workers and passengers.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the essential contribution of the flight attendants to this study. We also recognize and appreciate the vital role that the employer and Judith Murawski of the Association of Flight Attendants played in the investigation. Susan Edmiston and Louise Mehler of the California Department of Pesticide Regulation provided helpful review of a draft of the CDHS report on which this paper is based (CDHS, 2003). NIOSH funding provided crucial support to this investigation.

REFERENCES

Azaroff LS, Levenstein C, Wegman D. 2002. Occupational injury and illness surveillance: conceptual filters explain underreporting. Am J Public Health 92(9):1421–1429.

Berger-Preiss E, Koch W, Gerling S, Kock H, Klasen J, Hoffman G, Appel KE. 2006. Aircraft disinsection: exposure assessment and evaluation of a new pre-embarkation method. Int J Hyg Environ Health 209(1):41–56.

Bradberry SM, Cage SA, Proudfoot AT, Vale JA. 2005. Poisoning due to pyrethroids. Toxicol Rev 24(2):93–106.

Burgess WA. 1994. Philosophy and management of engineering control. In: Harris RL, Cralley L, Cralley L, editors. Patty's Industrial Hygiene and Toxicology, 3rd ed., volume III, Part A, Theory and Rationale of Industrial Hygiene Practice: The Work Environment. New York: J Wiley. 134 p.

Carlson DA, Hogsette JA, Kline DL, Geden CD, Vandermeer RK. 2006. Prevention of mosquitoes (Diptera: Culicidae) and house flies (Diptera: Muscidae) from entering simulated aircraft with commercial Air Curtain Units. J Econ Entomol 99(1):182–193.

CDHS. California Department of Health Services. 2003. Occupational Illness Among Flight Attendants Due to Aircraft Disinsection. Oakland (CA): CDHS Occupational Health Branch. Final Report. 44 p. Available from http://www.dhs.ca.gov/ohb/OHSEP/disinsection.pdf. Accessed 2007 Jan 12.

Coats JR. 1990. Mechanisms of toxic action and structure-activity relationships for organochlorine and synthetic pyrethroid insecticides [review]. Environ Health Perspect 87:255–262.

Edling C, Kolmodin-Hedman B, Åkerblom M, Rand G, Fischer T. 1985. New methods for applying synthetic pyrethroids when planting conifer seedlings: symptoms and exposure relationships. Ann Occup Hyg 29(3):421–427.

Flannigan SA, Tucker SB, Key MM, Ross CE, Fairchild EJ II, Grimes BA, Harrist RB. 1985. Primary irritant contact dermatitis from synthetic pyrethroid insecticide exposure. Arch Toxicol 56(4):288–294.

Fuortes L. 1999. Urticaria due to airborne permethrin exposure. [review]. Vet Human Toxicol 41(2):92–93.

Gebefügi I. 1989. Chemical exposure in enclosed environments. Toxikol Environ Chem 20–21:121–127.

Gratz NG, Steffen R, Cocksedge W. 2000. Why aircraft disinsection? Bull World Health Organ 78(8):995–1004.

He F. 1994. Synthetic pyrethroids. Toxicology 91(1):43–49.

He F, Wang S, Liu L, Chen S, Zhang Z, Sun J. 1989. Clinical manifestations and diagnosis of acute pyrethroid poisoning. Arch Toxicol 63(1):54–58.

Henningsen P, Zimmermann T, Sattel H. 2003. Medically unexplained physical symptoms, anxiety, and depression: a meta-analytic review. Psychosom Med 65(4):528–533.

House RA, Holness DL. 1997. Investigation of factors affecting mass psychogenic illness in employees in a fish-packing plant. Am J Ind Med 32(1):90–96.

IARC. International Agency for Research on Cancer. 1991. International Agency for Research on Cancer. Monographs on the evaluation of carcinogenic risks to humans. Occupational exposures in insecticide application, and some pesticides. Lyon (France): IARC; (IARC Monograph:53). 612 p.

Jones TF. 2000. Mass psychogenic illness: role of the individual physician. [review]. Am Fam Physician 62(12):2649–2653. 2655–2656.

Jones TF, Craig AS, Hoy D, Gunter EW, Ashley DL, Barr DB, Brock JW, Schaffner W. 2000. Mass psychogenic illness attributed to toxic exposure at a high school. N Engl J Med 342(2):96–100.

Keifer MC. 2000. Effectiveness of interventions in reducing pesticide overexposure and poisonings. [review]. Am J Prev Med 18 (4 Suppl.): 80–89.

Kilburn KH. 2004. Effects of onboard insecticide use on airline flight attendants. Arch Env Health 59(6):284–291.

Kolmodin-Hedman B, Swensson Å, Åkerblom M. 1982. Occupational exposure to some synthetic pyrethroids (permethrin and fenvalerate). Arch Toxicol 50(1):27–33.

Lessenger JE. 1992. Five office workers inadvertently exposed to cypermethrin. J Toxicol Environ Health 35(4):261–267.

Llewellyn DM, Brazier A, Brown R, Cocker J, Evans ML, Hampton J, Nutley BP, White J. 1996. Occupational exposure to permethrin during its use as a public hygiene insecticide. Ann Occup Hyg 40(5):499–509.

NAS. National Academy of Sciences, Committee on Air Quality in Passenger Cabins of Commercial Aircraft, Board on Environmental Studies and Toxicology. 2002. The Airliner Cabin Environment and the Health of Passengers and Crew. Washington DC: National Academ Pr. 344 p.

NIOSH. National Institute for Occupational Safety and Health. 2005. Case Definition for Acute Pesticide-Related Illness and Injury Cases Reportable to the National Public Health Surveillance System [online]. Cincinnati, OH: NIOSH; [updated 2005 Apr]. Available from http://www.cdc.gov/niosh/pestsurv/pdfs/pest-casdef2000.pdf. Accessed 2006 Nov 18.

Ray DE. 1991. Pesticides derived from plants and other organisms. In: Hayes WJ, Laws ER, editors. Handbook of Pesticide Toxicology, vol. 2; Classes of Pesticides. New York: Academic Pr. pp 585–636.

Ray DE, Forshaw PJ. 2000. Pyrethroid insecticides: poisoning, syndromes, synergies, and therapy. [review]. J Toxicol Clin Toxicol 38(2):95–101.

Spencer J, O'Malley M. 2006. Pyrethroid illnesses in California, 1996–2002. Rev Environ Contam Toxicol 186:57–72.

USDOT. United States Department of Transportation Federal Aviation Administration. 2004. The Air Curtain as an Approach to Aircraft Disinsection. Presented by the United States of America. In: The International Civil Aviation Organization (ICAO) 35th Assembly Meeting; 2004 Sep 28–Oct 8; Montreal. Agenda item 29: Facilitation. Available from http://www.faa.gov/international/35Assembly/DisinsectionIP.pdf. Accessed 2006 Jul 25.

USDOT. United States Department of Transportation. 2006. Aircraft Disinsection Requirements [online]. Washington DC: USDOT [updated 2006 Aug 29]. Available from http://ostpxweb.dot.gov/policy/safetyenergyenv/disinsection.htm. Accessed 2007 Jan 12.

USEPA. United States Environmental Protection Agency. 1996. EPA Pesticide Regulation Notice 96-3; 1996 May 14; Washington DC: USEPA Office of Pesticide Programs. Available from http://www.epa.gov/PR_Notices/pr96-3.html Accessed 2007 Jan 12.

USEPA. United States Environmental Protection Agency. 1997. List of chemicals evaluated for carcinogenic potential. Washington DC: USEPA. Available from Communication Services Branch (7506C), Office of Pesticide Programs, US Environmental Protection Agency, 1200 Pennsylvania Avenue, NW, Washington, DC 20460; phone (703) 305-5017.

USEPA. United States Environmental Protection Agency. 1999. Recognition and Management of Pesticide Poisonings. EPA 735-R-98-003. U.S. Environmental Protection Agency, Office of Prevention, Pesticides and Toxic Substances. 87–88.

USEPA. United States Environmental Protection Agency. 2001. U.S. Environmental Protection Agency. Office of Prevention, Pesticides, and Toxic Substances Charles Franklin, Chief, Communication Services Branch, Field and External Affairs Division. Letter to: flight attendant in response to flight attendant letter to Attorney General Janet Reno concerning health impacts of aircraft disinsection. 2001 Mar 7.

Weston DP, Holmes RW, You J, Lydy MJ. 2005. Aquatic toxicity due to residential use of pyrethroid insecticides. Environ Sci Technol 39(24): 9778–9784.

WHO. World Health Organization. 1985a. Safe use of pesticides. ninth report of the WHO expert committee on vector biology and control. World Health Organ Tech Rep Ser 720:1–60. 19.

WHO.World Health Organization. 1985b. Recommendations on the disinsecting of aircraft. Wkly Epidemiol Rec 60:45–52.

WHO. World Health Organization International Programme on Chemical Safety. 1995. Report of the Informal Consultation on Aircraft

Disinsection; Geneva, 6–10 November 1995. Geneva: WHO. WHO/PCS/95.51. 59 p.

WHO. World Health Organization Communicable Disease Control, Prevention and Eradication Pesticide Evaluation Scheme (WHOPES) & Protection of the Human Environment Programme on Chemical Safety (PCS). 2005. Safety of pyrethroids for public health use. Geneva: WHO. WHO/CDS/WHOPES/GCDPP/2005.10 WHO/PCS/RA/2005.1. 77 p. Available from http://whqlibdoc.who.int/hq/2005/WHO_CDS_WHOPES_GCDPP_2005.10.pdf Accessed 2006 Jul 13.

APPENDIX

Model of Pesticide Release In Aircraft Cabin

The purpose of the model was to estimate the air levels of permethrin during the 30-minute application period and during the 45-minute period after the application is completed. Using the model, two scenarios are evaluated: (1) no mechanical dilution ventilation is supplied to the aircraft; and (2) maximal dilution ventilation (11 air changes per hour) is supplied for 45 min. following the pesticide application.

Assumptions:

(1) a solution containing 2.2% permethrin (w/w) is applied with a fogger in the cabin;
(2) passenger cabin volume 1000 m^3;
(3) average cabin height of 6 ft;
(4) equal permethrin mass in the different particle sizes in the diameter range 5–40 μm;*
(5) uniform emission during the 30-minute spray period;
(6) no ventilation whatsoever in the cabin during the application.

*CDHS requested detailed information on particle size distribution from the manufacturer but data were not provided.

To begin, the model divides the particles into small diameter bins and uses the midpoint values. For example, there was a 5–6 μm bin (midpoint 5.5 μm), a 6–7 μm bin (midpoint 6.5 μm), and so forth up to the 39–40 μm bin (midpoint 39.5 μm). For each bin, the midpoint diameter value is used to compute the terminal settling velocity (m/min) for particles in that bin by: VTS = .0018 × (D^2), where the diameter D is in μm. This equation holds for a sphere of unit density (water), which is essentially what the pesticide solution is. A slip correction factor was not used because its effect on VTS is negligible for particles with aerodynamic diameters greater than 5 μm. The effective or average height H (in m) of the passenger cabin is assumed to be 1.83 m (6 ft).

$$\text{lambda1} = \text{VTS}/\text{H per minute for the particles in that bin} \quad (1)$$

The model assumes that each of the 35 bins contained 1/35 of the permethrin mass applied, and that the mass was applied (sprayed) in 30 min.. So in each bin, the mass emission rate (μg/min) into air was:

$$G = (\text{total mass}/35)/(30\ \text{min}) \quad (2)$$

During the spraying, it is assumed there is no exhaust ventilation. In each bin, the buildup in airborne concentration (μg/m^3) is computed by the equation:

$$C(t) = [G/(\text{lambda1} * V] \times [1 - \exp(-\text{lambda1} \times t] \quad (3)$$

where V is the passenger cabin volume (1000 m^3) and t is time in min. This equation holds from t = 0 to t = 30 min.

The total airborne concentration at any time is the sum of the concentrations for the 35 respective bins. At the end of spraying (t = 30 min), there is some total concentration. The model assumes the ventilation system was running for 45 min. and provided Q m^3/min of effective ventilation (11 ACH). For the Q value used, compute lambda2 = Q/V per minute.

In each bin, there was some initial concentration C (zero) equal to the C(30 min) value at the end of the spraying. In each bin, the decay in concentration (ug/m^3) is computed by the equation:

$$C(t) = C\ \text{zero} \times \exp(-[\text{lambda1} + \text{lambda2}] \times (t - 30)) \quad (4)$$

This equation holds from t = 30 min to t = 75 min., where t = 0 is the start of the spraying.

The total airborne concentration at any time is the sum of the concentrations for the 35 respective bins.

Note: A lower average cabin height would increase the rate of settling. Putting more of the mass in smaller particles would increase the airborne mass concentration, while putting more of the mass in larger particles would decrease the airborne mass concentration.

TABLE A1. Predicted Air Concentration of Permethrin (μg/m^3) by Quantity Applied and by Aircraft Ventilation Status

		Permethrin concentration 45 min. after application is completed (μg/m^3)	
Quantity of pesticide applied in aircraft cabin (L)	Permethrin concentration at the end of the application (μg/m^3)	No ventilation	11 Air changes per hour
20	62,862	4,130	1.1
22.8	71,663	4,704	1.2
29	91,150	5,988	1.6

34.4 L of a 2.2% solution of permethrin is applied to the aircraft. Approximately, 29 L is applied to the cabin, and 5.4 L is applied to the cargo hold. It is assumed that the application to the cargo hold does not impact air quality in the cabin.